

Performance Evaluation of the Approaches and Algorithms Using Hamburg Airport Operations

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Abstract – The German Aerospace Center (DLR) and the National Aeronautics and Space Administration (NASA) have been independently developing and testing their own concepts and tools for airport surface traffic management. Although these concepts and tools have been tested individually for European and US airports, they have never been compared or analyzed side-by-side. This paper presents the collaborative research devoted to the evaluation and analysis of two different surface management concepts. Hamburg Airport was used as a common test bed airport for the study. First, two independent simulations using the same traffic scenario were conducted: one by the DLR team using the Controller Assistance for Departure Optimization (CADEO) and the Taxi Routing for Aircraft: Creation and Controlling (TRACC) in a real-time simulation environment, and one by the NASA team based on the Spot and Runway Departure Advisor (SARDA) in a fast-time simulation environment. A set of common performance metrics was defined. The simulation results showed that both approaches produced operational benefits in efficiency, such as reducing taxi times, while maintaining runway throughput. Both approaches generated the gate pushback schedule to meet the runway schedule, such that the runway utilization was maximized. The conflict-free taxi guidance by TRACC helped avoid taxi conflicts and reduced taxiing stops, but the taxi benefit needed be assessed together with runway throughput to analyze the overall performance objective.

I. INTRODUCTION

In today's commercial aviation system, airport operation is a critical component that has great impact on system performance. According to a study of Air Traffic Management (ATM) operational performance conducted in 2013 by EUROCONTROL and Federal Aviation Administration (FAA) [1], airports contribute to 56% and 86% of total Air Traffic Flow Management (ATFM) delay in Europe and US, respectively. Insufficient capacity, operational uncertainties, and lack of coordination and information sharing among stakeholders and service providers lead to excessive taxi delay and missed opportunities to optimize resource utilization. According to [2], a total of 32 million minutes of taxi-out

delay and 13 million minutes of taxi-in delay were estimated at major US airports in 2009. Increased taxi delay translates to extra fuel burn and emissions. Domestic flights in the United States emit about 6 million metric tons of CO₂, 45,000 tons of CO, 8,000 tons of NO_x, and 4,000 tons of Hydrocarbons (HC) in total during taxi-out to runway takeoff [3]. In the European Aviation Environmental Report [4], the excess of CO₂ emissions generated by the inefficiency of the taxi-in and taxi-out phases in European airports is estimated at 229 kg per flight, or 2 million metric tons in total in 2014.

Airport operations impose many challenges due to complex processes and uncertainties. The need to improve airport operations in terms of operational efficiency, predictability, and throughput has drawn much attention within Air Navigation Service Providers (ANSPs) and the ATM research community across the Atlantic [5][6]. The lack of information sharing and coordination in airport operations is a driving motivation for the Collaborative Decision Making (CDM) concept that has recently been introduced into both European and US systems [7][8]. Both Airport-Collaborative Decision Making (A-CDM) in Europe and Surface-Collaborative Decision Making (S-CDM) in the US allow for planning of airport surface operations at a strategic level in order to meet the goal of demand/capacity balancing. In the A-CDM concept of operations, for instance, estimated landing times of arrival flights are continually sent to the airport by the Central Flow Management Unit (CFMU) of the Network Management Operations Center (NMOC) and used to update the subsequent (turnaround) outbound flight plan. The takeoff times (also known as target takeoff times) of the outbound flights, calculated by the A-CDM function, are sent to CFMU to compare with their departure (runway) slots and adjusted as necessary. On the other hand, tactical scheduling tools, which are the focus of this paper, provide advisories to Air Traffic Control Tower (ATCT) controllers and ramp/apron operators to support strategic decision-making and planning, and at the same time provide tactical decision support as flights prepare to depart. These advisories implement tactical schedules, e.g. gate pushback times, taxi operations, and runway departure

sequences that aim to reduce taxi delay while maximizing airport throughput under various operational constraints.

The German Aerospace Center (DLR) and the National Aeronautics and Space Administration (NASA) are independently developing and testing new concepts, algorithms and tools to address these challenges in airport operations. Both teams have succeeded in innovating and testing new concepts and algorithms in their respective airport systems. To leverage the knowledge and experience gained by each side, DLR and NASA agreed to collaborate on airport surface management research. This paper evaluates the approaches and tactical scheduling algorithms developed by DLR and NASA using a common airport, Hamburg Airport (EDDH) in Germany.

This paper is organized as follows. Section II provides a description of current day operations in Europe and U.S. airports. Section III presents the concepts, modeling and simulation tools independently developed by DLR and NASA. The simulation model development, common performance metrics, and evaluation of the two scheduling approaches and system setups for Hamburg airport surface operations are presented in Section IV. The paper ends with concluding remarks and suggestions for future work.

II. CURRENT DAY OPERATIONS AT EUROPEAN AND US AIRPORTS

This section provides a brief description of operations at US and European airports.

A. Definition of Airport Surface Areas

In a US airport, the movement area comprises runways, taxiways and other areas that are used for taxiing, takeoff, and landing. The FAA ATCT is in charge of traffic in the movement area. The terminal ramp area, called the non-movement area, includes gates and parking areas [9]. It is quite common that airlines lease gates and hence has exclusive control over all ground activities in the ramp area, including gate pushback. The transition of control between the ramp area and the movement area takes place at spots on the boundary of the two areas.

The movement area in a European airport, as defined by the International Civil Aviation Organization (ICAO), is part of the airport surface for pushback, takeoff, landing, and taxiing. The movement area consists of the maneuvering area and the apron(s) [10]. The maneuvering area, including taxiways and runways, is under the control of Air Traffic Control (ATC). The apron is either controlled by the airport operator, e.g., Frankfurt, Munich, and Hamburg Airports, or delegated to the ATC, e.g., Dusseldorf Airport.

B. Taxi In

While arrival aircraft are taxiing in, the transfer of control from the ATCT to the apron/ramp control occurs near the boundary of the taxiway and the apron/ramp area. The taxi-in

process ends when an aircraft completely stops at the gate or parking stand and its engines are off.

In the US, the ATCT controller issues a taxi clearance to a spot after the aircraft lands and exits from the runway. The aircraft is then asked to contact the ramp controller before the aircraft reaches the spot. Once the aircraft crosses the spot, control is handed to the ramp controller. Similarly, in Europe, the control hand-over from the ATCT controller to the apron controller usually takes place before the aircraft enters the apron area to avoid stopping the aircraft.

C. Turnaround

The flight turnaround is a complex process that spans the time between gate-in and gate-out, including all of the ground activities, such as passenger de-plane/boarding, baggage unloading/loading, fueling, and cleaning. The airline, the airport authority, or a third party handler, manages the turnaround process. Due to the uncertainties associated with this multi-step process, it is difficult to predict when the aircraft will be ready for departure from the gate. In the US, the flight operator does not have accurate flight ready time estimates. Therefore, the ramp controller relies on the pilot's request for pushback to make any planning decisions. Currently, John F. Kennedy International Airport (JFK) has implemented the Ground Management Program (GMP) based on a CDM concept to help mitigate the situation by requiring participating airlines to provide an estimated gate departure time or Earliest Off-Block Times (EOBT) of each flight to the system for departure scheduling. In A-CDM equipped European airports (e.g., Munich and Zurich airports), the Target Off-Block Time (TOBT) is the gate departure time guaranteed by the airline/ground handler.

D. Taxi Out

The aircraft taxi out process begins at gate pushback and ends at runway takeoff. In the US, a Pre-Departure Clearance (PDC) is issued by the Clearance Delivery position to the pilot 30 minutes prior to the proposed departure time. The pilots call the ramp to get a pushback clearance when the aircraft is ready to depart. Once pushback is complete, the pilots call the ramp for a taxi clearance. Control is transferred from ramp to ATCT at the designated spot, and the ground controller will issue a clearance to taxi to the assigned runway. As the aircraft approaches the runway, control is transferred to the local controller who issues line-up and takeoff clearances.

At A-CDM equipped airports in Europe, pilots are required to monitor Clearance Delivery and call in 5 minutes or less prior to TOBT to get an en-route and engine start-up clearance. Depending on the Target Start-up Approval Times (TSATs) and the traffic situation, the clearance is issued. The apron controller issues a pushback clearance at TSAT. The airplane is under the control of the apron controller until it reaches the border of maneuvering area, where the ground controller guides the aircraft to its assigned runway. The remaining taxi-out process is the same as that at the US airports.

E. Line-up and Takeoff

The procedures for line-up at the runway and takeoff are very similar in the US and Europe. It is common practice that aircraft receive takeoff clearances after line-up once the runway separation requirement is met. The runway separation requirement is determined by multiple criteria, including aircraft weight class and divergent heading based on Area Navigation (RNAV) routes.

F. Traffic Flow Management

Surface operations are affected by Traffic Flow Management (TFM) decisions. TFM related decisions are made to balance demand and capacity of air traffic in the entire airspace to minimize system delay and maintain throughput. The NMOC and the Air Traffic Control System Command Center (ATCSCC) are the two central authorities responsible for implementing TFM procedures in Europe and the US, respectively. In the US, the ATCSCC assigns takeoff times to the flights bound for the airport or sector where arrival rates are degraded due to heavy traffic volume or by adverse conditions such as bad weather. The assigned departure time, called Expected Departure Clearance Time (EDCT), has a compliance window of ± 5 min around the assigned takeoff time. Another TFM procedure called Miles-in-Trail (MIT) can be negotiated between Air Route Traffic Control Centers (ARTCCs) to limit the en-route traffic flow that in turn could impact airport departure throughput. Similarly in Europe, NMOC publishes departure constraints by issuing Calculated Takeoff Time (CTOT). A compliance window of -5 min/+10 min around CTOT has to be adhered to by the flight.

III. OPERATION CONCEPTS AND TOOLS BY DLR AND NASA

A. Simulation and planning tools of DLR

According to the Single European Sky ATM Research (SESAR) road map for modernizing air traffic management in Europe [11], a new generation of airport decision support systems has been introduced in the last decade. The Departure Management System (DMAN) and the Surface Management System (SMAN) are two of these airport surface systems that provide critical decision and execution support capabilities to controllers and flight deck.

DMAN's responsibility is to improve departure flows on the airport surface by providing the Target Takeoff Time (TTOT) and the TSAT for each departure under multiple constraints and airline preferences [12][13]. The Controller Assistance for Departure Optimization (CADEO) is DLR's implementation of DMAN [12]. It is an ATC tool that optimizes the departure takeoff sequence by calculating the TTOTs for each departure. Working without being coupled with SMAN, CADEO estimates the TSATs from TTOTs using the Variable Taxi Times (VTTs) provided by A-CDM. CADEO is a generic tool that can be adapted to different

airports. CADEO's departure sequence optimization takes into account the operational constraints at the airport, such as wake vortex separations based on aircraft weight category, runway occupancy times based on aircraft type, and miles-in-trail constraints for consecutive departures going to the same departure fix. Optimization objectives may include maximum runway throughput, departure slot time adherence, taxi-out delay reduction, and planning stability [13]. Through a series of real-time simulations conducted for Prague Airport [13], it was found that CADEO advisories helped reduce taxi times and stops and avoided excessive queues at the runway holding points.

The Taxi Routing for Aircraft: Creation and Controlling (TRACC) is DLR's prototype for SMAN [14]. TRACC generates optimal conflict-free taxi trajectories for all aircraft surface movement, including gate pushback. In the context of SMAN, a taxi trajectory differs from a time-based taxi route such that in addition to position and time, the trajectory also includes speed and acceleration information. TRACC provides the taxi guidance instructions to ATC controllers and potentially to the flight deck as well.

The concept of integrated CADEO-TRACC system was evaluated in recent studies [15][16]. The vision is to use TRACC to generate conflict-free taxi trajectories that meet the TTOTs prescribed by CADEO. The expected outcome was to improve taxi operations and gain experience in the integrated concept. In this integrated CADEO-TRACC concept, CADEO calculates departure TTOTs based on the Earliest Line-up Times (RLUTs) estimated from TRACC and derives the Target Line-up Times (TLUTs) as the target times for TRACC to deliver departure aircraft to the runway. Then TRACC calculates the optimized taxi trajectories starting from pushback and sets TSATs. Based on these taxi trajectories, Estimated Line-up Times (ELUTs) are computed and compared with the TLUTs. If ELUT is later than TLUT, TRACC will adjust the trajectory to meet TLUT, and if RLUT is later than TLUT, CADEO will re-plan TTOTs. TRACC optimizes TSATs to hold departures at the gate as long as possible and to reach the departure runway in time. The integration concept was first tested with the Munich Airport via simulations. The results confirmed the feasibility and potential benefits of integrated departure and surface traffic management [16].

Air traffic operations are simulated using the National Aerospace Laboratory (NLR) Air Traffic Control Research Simulator (NARSIM) [17]. NARSIM consists of four simulation systems (i.e., the air system, the ground system, the air/ground communication system, and the "meteo" system) and one control system. The air system generates realistic flight trajectories and facilitates communications between the simulated pilot and the aircraft model. The ground system creates an experimental environment for air traffic controllers to evaluate human-machine interfaces of advanced air traffic management functions. The air/ground system provides the inter-communication and synchronization between the air and the ground systems. The meteo system presents

meteorological data that contribute to the generation of realistic flight trajectories and weather radar observations. Under the supervision of an experiment leader, the control system supervises (i.e., initialize, reset, start, etc.) the entire experiment.

B. NASA's SARDA concept and experiment

NASA has recently developed the Spot and Runway Departure Advisor (SARDA) tool [18][19][20][21][22] to provide advisories to controllers to help improve airport surface operations. The original SARDA concept was developed as an ATCT control decision support tool and tested in human-in-the-loop (HITL) simulations for Dallas/Fort Worth (Texas) International Airport (DFW) [18]. It provided runway sequence advisories to the local controller and spot release advisories to the ground controller. It was a tactical tool aiming at reducing taxi delay by shifting delay from taxiways and runway queues to the ramp area without affecting airport throughput. The results from the initial simulations with SARDA showed reductions in taxi delay (45-60%) and fuel consumption (23% and 33%) in the movement area compared with non-advisory cases in both medium and heavy traffic scenarios.

In a study conducted in 2012, the SARDA advisory tool was integrated with a strategic scheduling component to support the S-CDM concept [19]. This strategic scheduling component provided a mechanism for the airline operator to share data and preferences with the SARDA system. The strategic scheduler received flight ready times within a predetermined planning window from the airline and then generated the target pushback times and spot release times. These times were communicated back to the airline for confirmation. The tactical scheduling component provided the advisories for spot release sequence to the ground controller as aircraft push back from the gates, and runway sequence advisories to the local controller as the aircraft join the runway queue. Integrating the strategic scheduling component in the overall scheduling process helps reduce the uncertainties of flight readiness and potential missed opportunities. The results from the study based on a real-time automated simulation for DFW showed reductions in both mean and variation in taxi delay under varying uncertainties in actual pushback times.

The most recent SARDA HITL experiment was conducted for Charlotte Douglas (North Carolina) International Airport (KCLT) through collaboration with American Airlines [20], where SARDA was used as a ramp controller decision support tool. Note that at KCLT, American Airlines is the dominant air carrier whose operations account for 85% of the entire airport operations. In addition, American Airlines manages the ramp tower. A series of HITL simulations were conducted where the SARDA system provided pushback advisories to the ramp controller, while no additional SARDA guidance was given to the local or ground controllers. The simulation results showed that the SARDA tool helped reduce taxi times on

average by one minute per flight without decreasing runway throughput. In addition, the advisories improved EDCT conformance and reduced ramp controller's workload.

The core component of the SARDA tool is its scheduler called the Spot Release Planner (SRP) [21]. It is a two-stage algorithm. The first stage is a runway scheduler. It takes a snapshot of the current surface traffic situation and calculates the optimized sequence and times for runway usage, including departure takeoff and aircraft waiting for crossing. The algorithm incorporates numerous constraints such as wake vortex separation and miles-in-trail restriction and can be solved for multiple objectives including maximum throughput and minimum system delay. The second stage determines times to release aircraft from gates or assigned spots to meet the previously calculated runway departure schedules. It uses predicted taxi times in the calculation. The simplest taxi time prediction can be based on a percentile of unimpeded taxi time distribution in historical operations. A recent study of taxi time prediction algorithms for KCLT operations revealed that fast-time simulation methods or machine learning techniques outperformed the method using unimpeded taxi times in terms of taxi time prediction accuracy [23].

IV. THIS WORK

This section discusses and evaluates the concepts and approaches of the two different surface traffic management systems developed by DLR and NASA, i.e., CADEO-TRACC and SARDA. The analysis was based on simulations using Hamburg Airport (EDDH) in Germany. To provide a common basis for the evaluation both systems were setup using a common airport model and a common simulation scenario. A common set of metrics was also used for performance assessment. It should be noted that the selection of Hamburg Airport was primarily due to the availability of extensive operational data. It was not the objective of this work to address particular operational challenges at Hamburg Airport.

A. Airport and traffic scenario

In this experiment, a two-hour traffic scenario that contained 35 departures and 34 arrivals for EDDH, as shown in Fig. 1, was created based on actual flight data on May 25, 2004. Out of the total 69 aircraft, 63 are of ICAO Medium wake category (e.g., A320 and B733). Calm winds and good visibility were assumed. EDDH has two intersecting runways: Runway 33 for departures and Runway 23 for arrivals. This is the most common runway configuration at EDDH. Arrivals exit from Runway 23 and cross the departure runway at a single location, entering the apron area to the gates. There are five runway exits on the left of Runway 23. The first one is a high-speed exit and the other four are standard ones. The gates and stands in Apron 1 (right of the runway crossing) are very close to Runway 33 entrances.

For the purpose of the experiment, it was assumed that all flights were under Instrument Flight Rules (IFR). Each departure had a Scheduled Takeoff Time (STOT) or wheels-off time, and each arrival had a Scheduled Landing Time

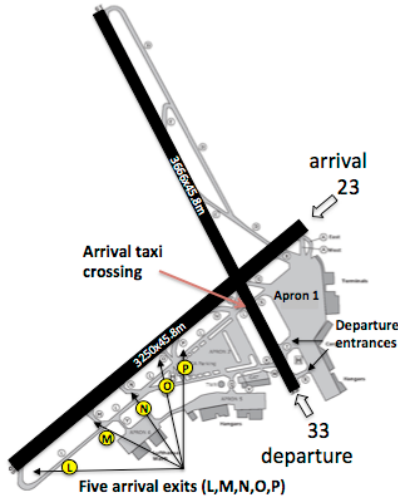


Fig. 1 Hamburg Airport [26]

Runway 33 is set at two minutes because of the required 4nmi straight ascent after takeoff by the Standard Instrument Departure (SID) for IFR flights.

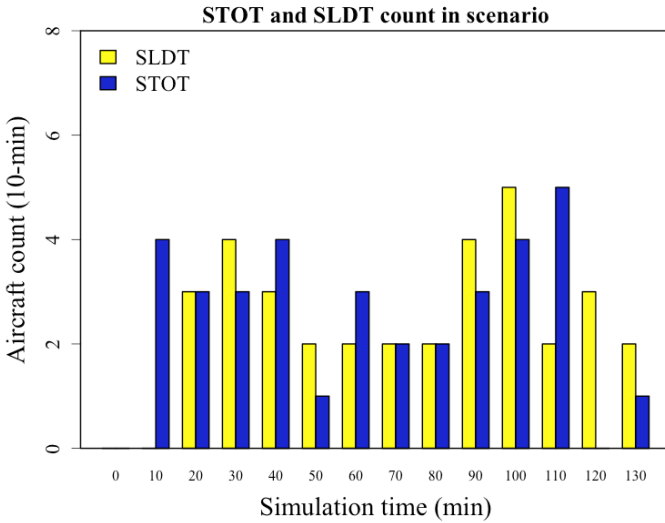


Fig. 2 SLDT and STOT count of the scenario

B. System setup of DLR simulation

An integrated system was setup and adapted for an automated real time (not HITL) simulation for EDDH (see Fig. 3). The system was comprised of CADEO, TRACC, NARSIM and SimNet. NARSIM generated the air traffic from the scenario, and was connected with CADEO and TRACC via SimNet to exchange planning information such as RLUT and TLUT. It executed the taxiing guidance received from TRACC. For this purpose, TRACC was equipped with an automated control interface to translate the commands into

instructions for the simulator. In HITL simulations, TRACC commands would be shown to the air traffic controller who then provided the advisories to the pseudo-pilot via radiotelephony.

Typical simulation events and the planning loop were as follows. When a departure flight approached its off-block time, it triggered the scheduling loop. First, TRACC calculates the RLUT using the standard taxi route and sends the RLUT to CADEO. Then CADEO computes optimal runway schedule with TTOT, considering overall runway traffic demands, and sends TLUT back to TRACC. According to the TLUT, TRACC attempts to create a conflict-free taxiing guidance to minimize stopping and waiting along the taxiways. CADEO's objective is to maximize the runway throughput by optimizing the TTOTs/TLUTs, and TRACC provides the advisory for aircraft movement to meet the runway schedule while minimizing taxi delays.

Because of the dynamic bi-directional coordination of CADEO and TRACC, an aircraft is subject to schedule time

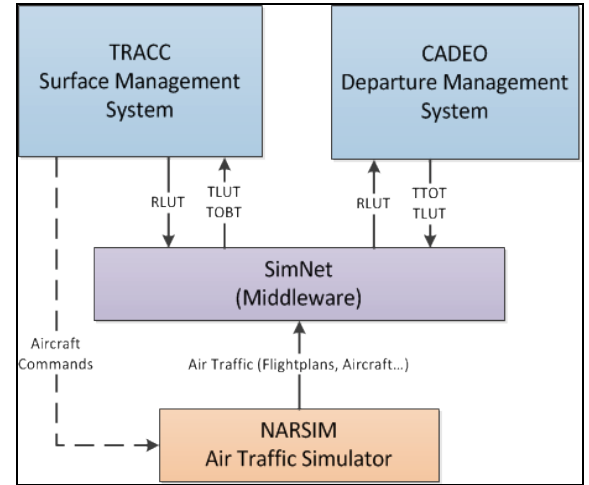


Fig. 3 System setup of DLR for Hamburg airport

change until it takes off or arrives at the gate. If TRACC receives new flight plans entering the planning horizon or there are aircraft that deviate from their assigned taxi trajectories, recalculations are necessary, and CADEO is notified and adjusts the runway schedule accordingly.

Table 1 explains five schedule update stages. For all stages except for "standard routes," optimization and conflict detection are performed. For the performance evaluation introduced in this paper, the schedule at "Last Optimization" was chosen for arriving and departing aircraft. It is the latest dataset for every flight because no optimization was performed beyond that and, therefore, represents the actual traffic situation influenced by the optimization of the planning tools.

The nominal taxi speed (i.e., the speed at which aircraft taxi unimpeded by other traffic) is based on the airport area (high-speed and normal taxiway, apron, pushback at the gate). The nominal taxi speed was set to 50, 30, and 15 kts for high-speed taxiways (e.g., runway exit), regular taxiways and

apron, respectively. Pushback was performed with 5 kts of taxi speed. The initial selection of runway exit for arriving aircraft was made based on the results of a probability calculator [29]. There, the probabilities of landing distances are assigned to weight classes. In combination with the air traffic simulator NARSIM, runway exits can be changed occasionally and TRACC accepts the new runway exit.

Table 1. Schedule update stages of CADEO-TRACC coordination

Schedule update stage	Definition
Standard Routes (no optimization, no conflict detection and resolution)	Predefined route set based on assumptions like fastest, shortest routes or standard routes in use at the observed airport.
First Optimization	Optimization for getting the first possible Line-up time
First Optimization with TLUT by CADEO (Departures only)	First optimization with a target takeoff time given by CADEO.
Last Optimization before Pushback (Departures only)	Optimization with the last adjustment of TSAT as response to a changed target takeoff time by CADEO. After that the TSAT would not change anymore.
Last Optimization	Last optimization done by TRACC for the observed aircraft.

C. SARDA system setup

The SARDA system setup for this study is shown in Fig. 4. NASA's fast-time simulator, called the Surface Operation Simulator and Scheduler (SOSS) [24][25], was used together with a SARDA scheduler implemented for the EDDH airport model.

SOSS models surface operations of flights, including flight

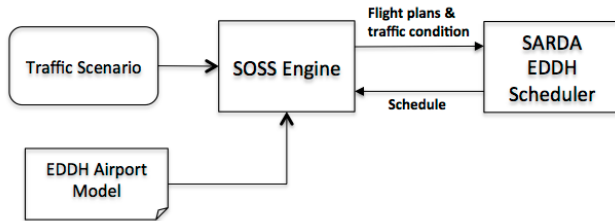


Fig. 4 Hamburg airport system setup for SARDA

readiness, pushback, taxi, takeoff, and landing. It uses a node-link graph to represent locations and connections of gates, ramps, taxiways, runway crossings and runways. EDDH node-link graph in SOSS was adapted from the same EDDH node-link model from DLR's Airport Data Editor for NARSIM. SOSS uses a set of rules to maintain appropriate separations of aircraft in runway operations such as takeoff, landing, and crossing. These rules are dependent on airport runway geometry. For EDDH operations in this study, the runway separation rules included: 1) consecutive departures at Runway 33, 2) departure and arrival at Runway 33 and Runway 23 (i.e., intersecting runway operations), and 3) taxiing arrivals that cross Runway 33 to enter the apron area.

Consecutive arrivals at Runway 23 were spaced in the traffic scenarios. The separation parameters followed the standard ICAO separation requirements based on aircraft weight class (wake category). For instance, a departure following a heavy aircraft (e.g., Airbus A330) requires more separation than a lighter aircraft (e.g., E110). The SOSS landing and takeoff models produced runway events such as wheels on/off and threshold crossing. Separation in runway operations was based on these events in simulation. The landing model selected appropriate exits for arrivals based on their aircraft types and the distances of exits from the runway threshold. In this EDDH simulation, all arrivals made exits at either the third (M) or the fourth exit (N). On the movement area (i.e., taxiways and apron), SOSS uses its internal Conflict Detection & Resolution (CD&R) logic with a First-Come, First-Served (FCFS) rule to move aircraft and maintain a proper separation among them. When two aircraft are predicted to have a taxi conflict such as in lead-follow or crossing situation, the one ahead is allowed to continue and the aircraft behind has to slow down or wait. The logic is strictly within a small-localized area and is designed not to interfere with strategic taxi schedules. The nominal taxi speed (i.e., the speed at which aircraft taxi unimpeded by other traffic) is aircraft type based. Because in this simulation, almost all aircraft are in the Medium category, the nominal taxi speed was averaged at 15 kts, and 10 kts in taxiway and apron, respectively. Pushback speed was set at 5 kts.

The SARDA Hamburg scheduler was an implementation of the SARDA concept for the study. It was a tactical planner and consisted of a runway scheduler and gate pushback planner. The runway scheduler created an optimized runway departure schedule for Runway 33 with maximum runway throughput as the objective. The constraints to the optimization algorithm were the arrival operations on Runway 23 that affect the departures from Runway 33 due to their intersecting runway geometry, as well as the departure wake vortex separation requirements. Arrivals crossing at Runway 33 were given a lower priority to help boost departure throughput.

During simulation, SOSS sent to the scheduler the surface traffic situation information (e.g., the aircraft positions and the latest runway operations) and flight plans (e.g., STOT). The scheduler calculated the best runway departure schedule and pushback times, and sent them to the simulator. Standard taxi routes and nominal taxi speeds were used. One key difference from the CADEO and TRACC system is that the taxiing schedule was time-based only and not guaranteed conflict free. SOSS resolved potential taxi conflicts using the FCFS rule, which is similar to what a human controller does to resolve conflict situations [31].

D. Performance metrics

To make a meaningful assessment of the two different concepts and tools, a set of common performance metrics were first defined and agreed upon. These metrics, shown in Table 2, were derived from the ICAO's Key Performance

Areas (KPAs) [27] and the Civil Air Navigation Services Organization (CANSO) [28]. Two KPAs were included in this study: capacity (one metric) and efficiency (four metrics).

Table 2. Performance metrics

Metric	Definition	KPA
Departure runway throughput	Number of takeoffs (wheels-off) at Runway 33 in 10-minute interval	Capacity
Departure taxi time	Time from pushback start to runway takeoff roll position, excluding waiting time for takeoff clearance	Efficiency
Push back delay	Difference of actual off block (pushback start) time and flight ready time	Efficiency
Departure line-up queue time	Time spent in departure queue area (and part of departure taxi time), excluding waiting time for takeoff clearance	Efficiency
Arrival taxi time	Time from arrival aircraft runway exit runway until arriving at gate	Efficiency

E. Simulation Results and Evaluations

The following results and evaluations are guided by the metrics outlined in Table 2. The terms CADEO-TRACC and SARDA thereafter are used to refer to the two simulation system setups, respectively.

As discussed previously, the study included the same airport, the same simulation scenario, the same metrics but different simulation systems. The differences were not only in the scheduling and taxi concepts implemented, but in the simulators as well (real-time versus fast-time). Noticeably, CADEO-TRACC's nominal taxi speed was configured at 30 and 15 kts for taxiway and apron, whereas SARDA was at 15 and 10 kts. CADEO-TRACC used the first two arrival exits at Runway 23 while SARDA chose the third and fourth exits.

1) Departure runway throughput

Fig. 5 shows the departure throughputs on Runway 33. The numbers of departures (i.e., wheels-offs) are counted in a 10-minute interval during the less than 2.5 hour-long scenario. For reference, the STOTs are included. In the first 1.5 hours, both systems produced very similar throughput levels. The obvious difference occurred in the last 40 minutes, where CADEO-TRACC's throughput lagged. Although both schedulers of the two systems sought the maximum departure throughput, the means of delivering aircraft to the runway were different. SARDA in this experiment used an optimistic taxi time estimate from gate to runway to keep runway queue pressure. The planning process between CADEO and TRACC allowed negotiation between throughput and taxiing efficiency. By avoiding runway queues and taxi stops, TRACC might not be able to fill emerging gaps because the departures that could have been scheduled for these times

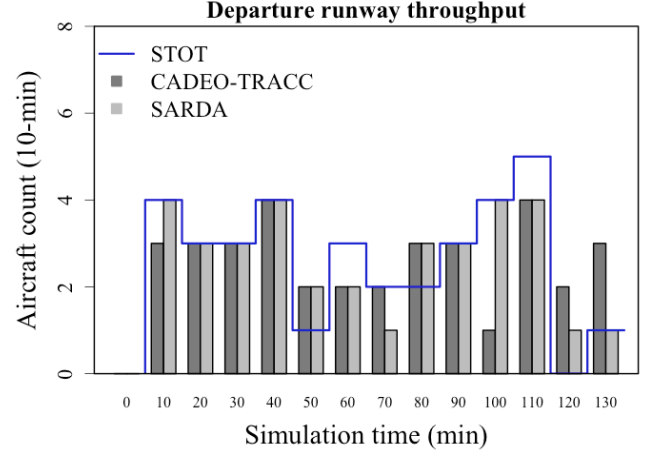


Fig. 5 Departure runway throughput

were planned to later departure times by CADEO-TRACC in order to achieve better taxi efficiency.

2) Taxi times

Taxi time is an important performance metric to measure taxi efficiency. Fig. 6 displays the total taxi times of departures and arrivals. The total taxi time is the summation of all aircraft taxi times.

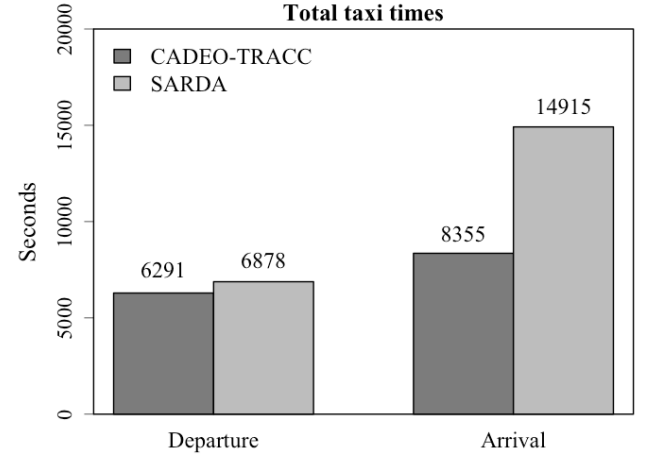


Fig. 6 Total taxi times

It is evident CADEO-TRACC used less taxi times than SARDA, in both departure and arrival categories. However, comparing these numbers directly would be biased because of the different taxi speed setups. To get a more equal assessment, a normalized taxi time method is used. The normalized taxi time is the taxi time divided by its unimpeded taxi time. The unimpeded taxi time is the time an aircraft taxi at nominal speeds unimpeded. Unimpeded time is a lower bound taxi time. In SARDA where aircraft never taxi above their nominal speeds, unimpeded time is the lower bound taxi benchmark. Since the two systems had their own nominal taxi speeds, their unimpeded taxi times are different. Table 3 shows the total unimpeded and normalized taxi times. SARDA had the longer unimpeded times because of its lower

nominal taxi speeds. The difference between the two simulations was less dramatic in departure than in arrival taxi times because the apron is very close to the runway entrances. The long taxiway for arrivals from Runway 23 combined with the fact that TRACC chose the first two runway exits (O, P) (i.e., shorter taxi distance to the apron) made a big difference in arrival unimpeded taxi times. Nonetheless, the normalized taxi times show that CADEO-TRACC performed closer to its

Table 3. Unimpeded and normalized taxi times

	CADEO-TRACC	SARDA
Departure unimpeded taxi time	6,178 seconds	6,640 seconds
Arrival unimpeded taxi time	7,884 seconds	12,877 seconds
Departure normalized taxi time	1.018	1.036
Arrival normalized taxi time	1.06	1.16

unimpeded taxi times than SARDA. This indicates that TRACC's conflict-free taxi guidance resulted in efficient surface movement for both departures and arrivals. On the other hand, the SARDA system relied on the fast-time simulator to resolve taxi conflicts, thus leading to taxi slow downs and stops, particularly in the apron area.

Fig.7 shows the boxplots for both departure and arrival taxi times. CADEO-TRACC's taxi times showed less variation (i.e., the 1.Qu and 3.Qu were closer to the median) than SARDA's taxi times. It seems to indicate that the conflict-free taxiing sought by the CADEO-TRACC would lead to better taxi time predictability or less uncertainty. Predictability, not measured in this study, is one of the important ICAO KPAs.

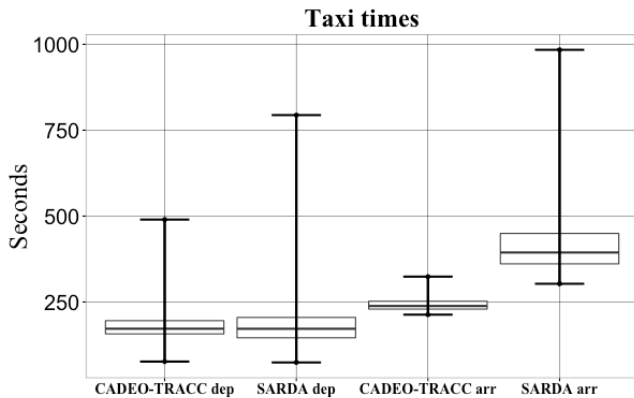


Fig. 7 Taxi time quartiles

3) Pushback delay and departure queue time

Figs. 8 and 9 show the pushback delays (i.e., gate holding) and departure queue times. The CADEO-TRACC held departures at gate/stand much longer than the SARDA did, 149 (5218/35 departures) to 38 seconds on average. This supports the finding discussed in Section 1): the CADEO-TRACC tend to keep aircraft longer at gates/stands to achieve conflict-free taxiing, which benefits the taxi efficiency and, at the same time, reduces the departure queue time at the

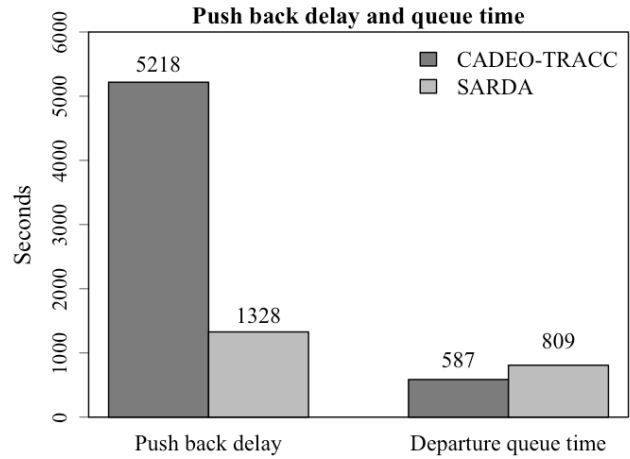


Fig. 8 Total Pushback delay and departure queue time

runway. The maximum of 946 seconds of gate holding by CADEO-TRACC that occurred during the last 30-40 min in

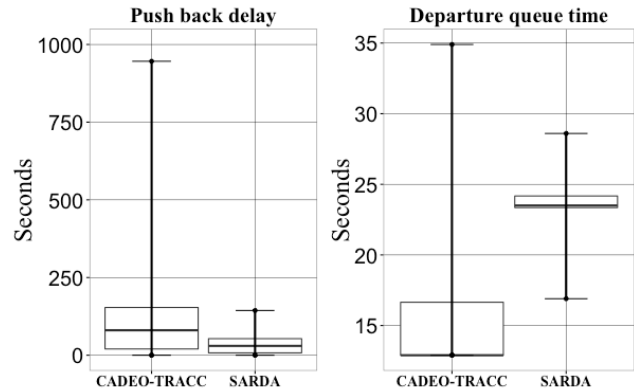


Fig. 9 Pushback delay and queue time quartiles

simulation was probably due to the peak demand of arrivals taxiing into the apron at the time (see Fig. 2).

The departure queue was defined as ~100 meters towards the runway line-up (takeoff) position. The average queue time was 17 (587/35 departures) for CADEO-TRACC and 23 seconds for SARDA. This is consistent with the pushback delay metric, meaning that more potential queue delay was shifted to gate holding by both systems. Moving taxi and queue delay to gate holding would reduce fuel burn and pollution (a metric in ICAO's environment impact KPAs).

F. Further Evaluations and Discussion

Other performance metrics can be derived and evaluated using the metrics already discussed. For departures, takeoff delay, which is defined as the difference between the actual takeoff time and the earliest possible takeoff time, can be considered. Since the earliest takeoff time can be calculated by adding the unimpeded taxi time to the scheduled pushback time (or flight readiness time), the takeoff delay is the same as the sum of pushback delay and taxi-out delay (between actual and unimpeded). From Figs. 6 and 8, and Table 3, the takeoff

delay values for CADEO-TRACC and SARDA are 5,331 ($=5,218+113$) and 1,566 ($=1,328+238$) seconds, respectively, shown in Fig. 10. Because the CADAO-TRACC tends to hold departures at gate/stand for a longer time in order to find conflict-free taxi trajectories, the takeoff times are also delayed, which is consistent with the departure throughput result shown in Fig. 5.

From the perspective of both departure and arrival operations, total system delay can also be calculated. The total system delay is defined as the sum of takeoff delay and taxi-in delay. The system delays for CADEO-TRACC and SARDA are computed as 5,748 and 3,664 seconds, respectively (see Fig. 10). Since the two systems have different unimpeded taxi speeds and times, the emphasis of this metric is to show the balance between departures and arrivals when scheduling surface traffic having intersecting runways. In the CADEO-TRACC simulation, the system delay was dominated by gate holding and in the SARDA simulation both gate holding and arrival delay had more comparable contributions to the system delay. Considering the delay propagation, a long queue of arrivals crossing the active departure runway should be avoided, and excessive pushback delay is also undesirable.

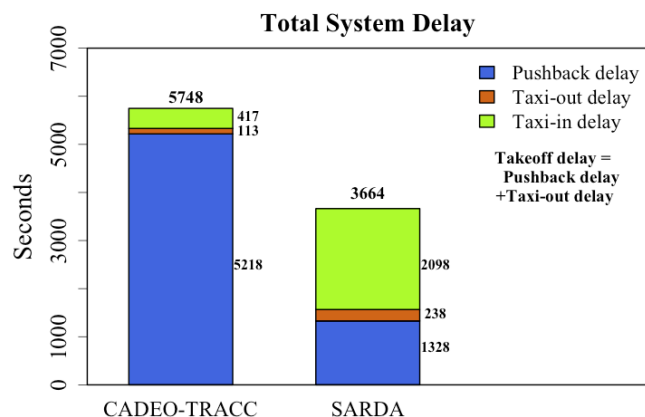


Fig. 10 Total system delay

The numbers and analysis thus far indicate the different approaches and results of the two simulations. The CADEO-TRACC's conflict-free taxi solution aimed to push the taxi efficiency closer to unimpeded performance. This strategy appeared to associate with larger taxi speed range (i.e., 30/15 kts nominal speed setups) and longer gate holding. A larger taxi speed range made it easier for TRACC to find solutions in conflict-free taxiing resolution space. Longer gate holding seemed to happen at the peak of the arrivals, which led to longer takeoff delays and therefore impacted departure throughput (Figs. 5 and 10). In addition to a good taxi time performance, the conflict-free taxi time distributions showed less variation, which would result in good taxi time prediction, another important performance metric for airport operation but not included in this study. The CADEO-TRACC's approach is a futuristic concept, and the SARDA's concept was based on current and near-term technologies. Both approaches focused on the throughput and efficiency improvement. The results

showed a good departure throughput and taxi performance balance of SARDA but less efficiency in departure taxi time reduction compared to CADEO-TRACC.

V. SUMMARY AND FUTURE WORK

This work is the first attempt to evaluate two different airport traffic management concepts and tools developed by DLR and NASA research teams. Two independent simulations were conducted using a simulation model of Hamburg Airport in Germany. One was a real-time simulation of the integrated CADEO-TRACC system conducted by DLR. The other was a fast-time simulation using the SARDA planning concept by NASA. Both systems were developed for the improvement of taxi efficiency while maintaining the runway throughput. A main difference between the two approaches is that the CADEO-TRACC system employs conflict-free optimized taxi guidance to reduce taxi stops while SARDA calculates pushback schedules by subtracting nominal taxi time from the optimized runway schedule. The planning cycle of the CADEO-TRACC system involves iterations between the two components (i.e., departure management and surface management), and allows negotiation between runway target times and taxi efficiency. This approach effectively takes the taxi conflicts into consideration in the runway scheduling. The SARDA system consists of a runway scheduler and gate pushback or spot release advisory depending on whom the advisories are provided to. In this work, the gate pushback schedule was calculated from the runway schedule that optimized at maximum runway throughput and the simulator executed pushback advisories. SARDA's runway scheduler objective is similar to that of CADEO. The taxi guidance of the SARDA system is limited to the release time at gate in this study, where the taxi conflicts are resolved by the simulator rather than by the scheduling algorithm.

The two simulation outputs are evaluated using a set of common performance metrics adapted from two of the ICAO's KPAs: capacity and efficiency. The results showed that both CADEO-TRACC and SARDA were able to improve taxi efficiency while maintaining runway throughput under a normal traffic conditions. The CADEO-TRACC had better taxi efficiency performance due to the conflict-free taxiing capability of TRACC. The strategy to incorporate taxi conflict avoidance into the runway and taxi planning might lead to longer gate holding in order to obtain conflict-free taxi solutions and, consequently, impacted runway throughput and cause potential gate conflicts with arrival aircraft. The SARDA system, on the other hand, allowed maintaining a small number of aircraft in the runway queue in order to prevent the runway from starving and reducing runway throughput.

Future work under the research collaboration between DLR and NASA includes investigating the scalability of the two approaches, especially the integrated CADEO-TRACC system, by testing at a much busier hub airport than Hamburg. Also, robustness and resilience of the systems will be

investigated under varying degrees of uncertainties and operational constraints. Lastly, the future research plan includes integration of the TRACC conflict-free taxi capability with the SARDA runway scheduler in SOSS and conducting fast-time simulations for a major US airport. This would help investigate the feasibility of introducing the trajectory-based taxi operation concept [30] and evaluate its benefit for US airport surface operations. This concept is a critical technology advance in not only addressing current surface traffic management problems, but also having potential applications in operations of unmanned vehicles on the airport surface.

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